ICIC Express Letters ICIC International ©2016 ISSN 1881-803X
Volume **10**, Number **10**, October **2016** pp. **2513–2520**

THE VACUUMING ASSISTANCE METHOD FOR THE LOWER-LIMB HANDICAPPED BY ILSR

Bo Shen and Shuoyu Wang

School of Systems Engineering
Kochi University of Technology
185 Miyanokuchi, Tosayamada, Kami, Kochi 782-8502, Japan
{ shen.bo; wang.shuoyu }@kochi-tech.ac.jp

Received March 2016; accepted June 2016

Abstract. *A vacuuming assistance method on independent life support robot (ILSR) is proposed in this paper for the lower-limb handicapped. Based on distance type fuzzy reasoning method (DTFRM), the proposed method is able to reason user's vacuuming intention according to upper body motion information during the vacuuming task. According to the reasoned task intention, assistance motion of ILSR is planned and by tracking the planned assistance movement, ILSR takes the lower-limb handicapped to move in his/her intended position. Vacuuming task experiments were implemented to verify the effectiveness of the proposed method and the results showed that the proposed method can support subjects to perform vacuuming task independently without any operation by hand.*
Keywords: Independent life support robot, Activity of daily life, Distance type fuzzy reasoning method

1. **Introduction.** As the aging of society around the world, more and more elderly are suffering from weakened walking capability or even bedridden with lower-limb handicap. On the other hand, because of diseases or accidents, a number of people lost the walking ability and become lower-limb handicapped. Most of them cannot live without caregivers any more. However, the declining birthrate of society leads to the insignificance of caregiver. It becomes more and more difficult for the lower-limb handicapped to receive health care. Even though they can take health care in daily, the long-term bedriddenness always causes disuse syndrome, which damages their health or even cuts down their life early. However, most of the lower-limb handicapped cannot walk by themselves, though their upper bodies are healthy enough to participate in daily tasks. Therefore, if robots can provide them with moving support in some way, they are able to live a healthier and independent life.

In the former research [1], a task intention method was developed for 7 ADLs of the lower-limb handicapped. For providing practical life support for the lower-limb handicapped, vacuuming task, one of the 7 tasks, was selected to be investigated in this work based on an independent life support robot (ILSR) [2] developed in our laboratory. By operating the joystick, user can manipulate the robot easily. For vacuuming assistance, tremendous work was done academically and commercially, such as Roomba [3] and Rulo. Compared with these vacuum cleaner robots, the proposed method on ILSR of this paper has 2 main advantages. 1) Active participation of healthy upper body in vacuuming task. 2) The proposed method can be extended to more tasks assistance in ADLs. By participating in vacuuming task positively, the lower-limb handicapped can get rid of disuse syndrome and even promote their health condition. Via compensating their walking ability by ILSR, they can perform more tasks of daily life independently. In order to provide the proper assistance movement by ILSR, user's task intention is necessary for planning the assistance movement. For identifying human intention, EEG [4], EMG [5], eye-track method [6], etc., were studied widely in many researches. The basic idea of the intention reasoning is that people have the same vacuuming intention while they do the same motion of their upper body during the vacuuming task. Based on the assumption, distance type fuzzy reasoning method (DTFRM) was utilized in the intention reasoning algorithm [7]. Meanwhile, assistance movement of ILSR can be planned according to the reasoning result of user's vacuuming intention as well. The proposed system is as shown in Figure 1.

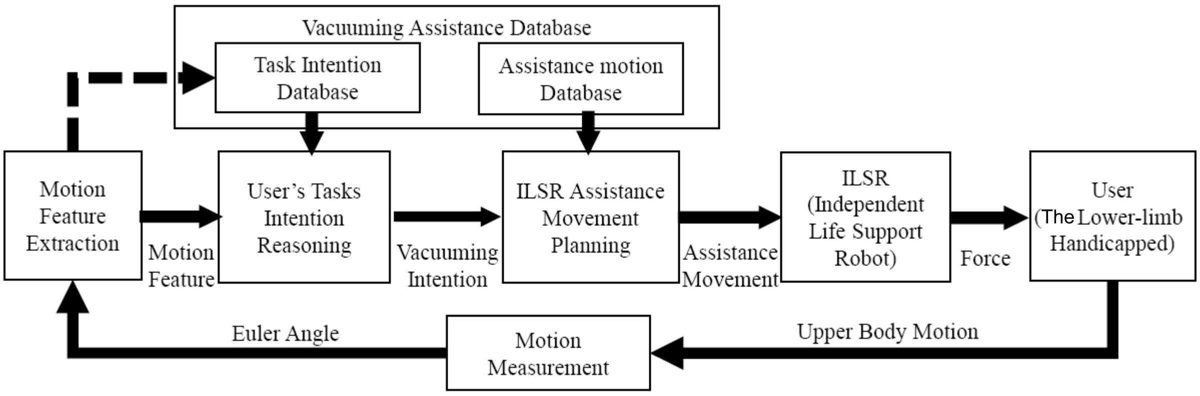


FIGURE 1. Independent life support system for vacuuming task

In addition to this introductory section, this paper is organized as follows. Section 2 presents a description of independent life support system, including the motion sensors and ILSR. In Section 3, the details of vacuuming task assistant method were proposed, including the procedure of establishment of database and planning algorithm of assistance motion of ILSR. In Section 4, a vacuuming task experiment was implemented to verify the effectiveness of the proposed method. Finally, a brief summary is presented in Section 5.

2. **Independent Life Support System.** The independent life support system contains 2 main parts in hardware: upper body motion detection system and ILSR. Upper body motion detection system is utilized for acquiring user's upper body motion, as shown in Figure 2.

2.1. **Motion detection system.** 5 motion sensors were attached on user' upper body to measure motion as shown in Figure 2. 4 of the motion sensors were positioned to the middle of user's upper and lower arms (Sensors 1, 2, 4, and 5), while 1 sensor was centered on the user's back (Sensor 3), slightly below the scapula.

2.2. **Kinematics of ILSR.** The coordinate system of ILSR was set up in Figure 3. In this figure, $\Sigma(x_r, y_r, O)$ is reference coordinate system fixed on the ground, and $\Sigma(x_b, y_b, C)$ is body coordinate system fixed on the robot. θ is orientation angle and v_i is velocity of each omnidirectional wheel, where $i = 1, 2, 3$. Similarly, W_i is omnidirectional wheels, and l is the distance between geometric centre C and omnidirectional wheels W_i ($l = 0.3$m).

The kinematics equation in robot body coordinate $\Sigma(x_b, y_b, C)$ was established.

$$v = T_b \cdot \dot{X}_C^b \tag{1}$$

where,

$$v = \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix}, \quad T_b = \begin{bmatrix} -\cos 2\pi/3 & \sin 2\pi/3 & L \\ -\cos 2\pi/3 & -\sin 2\pi/3 & L \\ 1 & 0 & L \end{bmatrix}, \quad \dot{X}_C^b = \begin{bmatrix} \dot{x}_C^b \\ \dot{y}_C^b \\ \dot{\theta} \end{bmatrix}$$

Then the wheel velocity v is expressed by ILSR's velocities $\dot{X}_C^b$ in Equation (1).

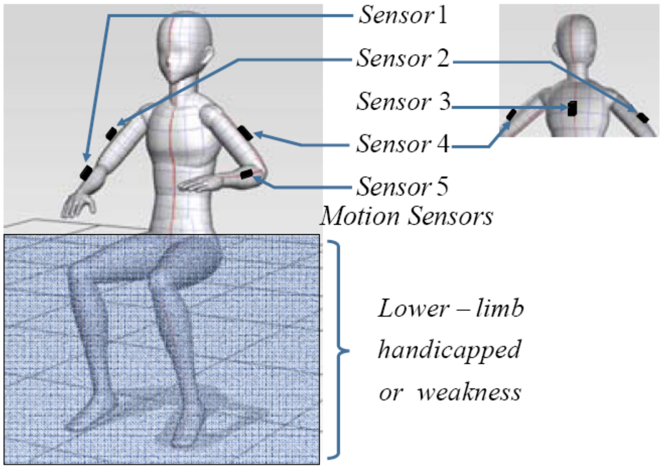


FIGURE 2. Placement of motion sensors

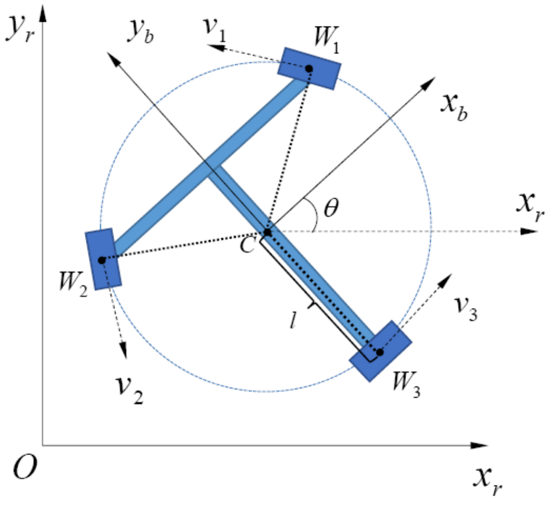


FIGURE 3. Coordinate system of ILSR

3. **Vacuuming Assistance Method by ILSR.** In order to provide vacuuming assistance for the lower-limb handicapped, the vacuuming assistance method contains 3 main parts. At first, the assistance necessary intentions were investigated.

3.1. **Vacuuming task intention.** By observing the vacuuming process of 5 health subjects, 2 fundamental behavior patterns of vacuuming task execution were found out.

Pattern 1: People prefer to clean the nearest position in sight.

Pattern 2: People always turn orientation to face the ground, where they intend to clean.

According to these 2 behavior patterns of vacuuming task, 3 inevitable intentions for vacuuming task were considered and can be described in the form of if-then rules.

3.2. **Establishment of vacuuming assistance database.** In order to provide vacuuming task assistance, the intention-behavior relationship of vacuuming task is described by *if-then* rules as follows.

Rule^1: *If* user's intention is cleaning the front area, *Then* ILSR moves forward (m^1).

Rule^2: *If* user's intention is cleaning the left area, *Then* ILSR turns left (m^2).

Rule^3: *If* user's intention is cleaning the right area, *Then* ILSR turns right (m^3).

Based on ***Rule***^{1}, ***Rule***^{2} and ***Rule***^{3}, ILSR can make the proper decision when subjects have vacuuming intention. For coping with the situation where subjects have no vacuuming intention, another rule was added to the database.

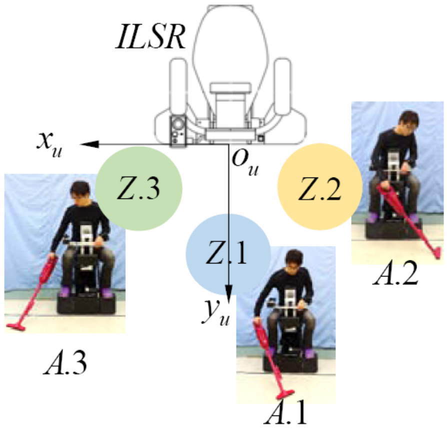


FIGURE 4. Vacuuming motion

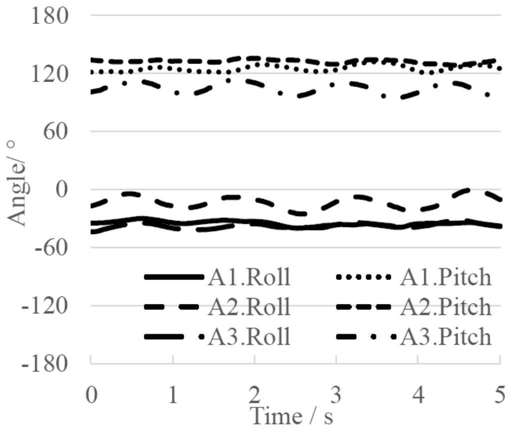


FIGURE 5. Euler angle of right forearm during vacuuming task

Rule^4: *If* user's intention is not vacuuming, *Then* ILSR keeps still (m^4).

In these 4 *if-then* rules, user's intention and ILSR's motion are the linguistic variables. According to the assumption proposed in Section 1, user's intention can be inferred from vacuuming motion of upper-body.

As shown in Figure 4, subjects were instructed to perform natural motion of vacuuming (A.1, A.2 and A.3) when they have the intention of cleaning the front area (Z.1), left area (Z.2) and right area (Z.3). In Figure 5 the right forearm motions measured by motion detection systems are presented in the form of gesture by Euler Angles. The gestures are similar during the test, but different from each other. In this work, 1.6 seconds moving window was applied for the normalized motion information to calculate the moving average and the standard deviation of this duration as the motion features.

The task intention database concluding subject's motion features of vacuuming task was established for vacuuming intention reasoning. For providing practical moving support, the assistance movements m^i $(i = 1, 2, 3, 4)$ of ILSR are quantified as shown in Table 1. The movements were determined by experiments. In the future, it will be adaptable by user's will.

3.3. **Vacuuming intention reasoning and assistance motion planning.** In the real condition of vacuuming task, user's vacuuming motions are continuous normally. Therefore, user's vacuuming intention is not only 4 categories in the *Rule*^{i} $(i = 1, 2, 3, 4)$. In order to reason out user's continuous vacuuming intention, the vacuuming intention reasoning and assistance motion planning method was developed on DTFRM. In DTFRM, the distances between fact and each rule are calculated at first, and then the reasoning

Table 1. Qualified assistance motion of ILSR

	Motion of ILSR	ILSR Speed $\dot{X}_C^b$ in robot body coordinate
m^1	ILSR moves forward	$(0\text{m/s}, 0.1\text{m/s}, 0°/\text{s})^T$
m^2	ILSR turns left	$(0\text{m/s}, 0\text{m/s}, 10°/\text{s})^T$
m^3	ILSR turns right	$(0\text{m/s}, 0\text{m/s}, -10°/\text{s})^T$
m^4	ILSR keeps still	$(0\text{m/s}, 0\text{m/s}, 0°/\text{s})^T$

result could be concluded from the distances between fact and each rule. 3 main steps of vacuuming intention reasoning and assistance motion planning by DTFRM is as follows.

Step 1: Calculate the distance of fuzzy sets. Fact and rules are all presented by fuzzy singletons in this work. The distance of 2 fuzzy singletons is defined as Equation (2).

$$d\left(A_{jx}^i, S_{jx}\right) = |a - b| \tag{2}$$

Step 2: Figure out the distance between fact and each rule.

$$d^i = \left(\sum_{j=1}^{5}\left[d^2\left(A_j^i, B_{jA}\right) + k \cdot d^2\left(D_j^i, B_{jD}\right)\right]\right)^{\frac{1}{2}} \tag{3}$$

In order to improve the reasoning capability for moving motion and still motion, a parameter k was added in Equation (3) to the distance of standard derivation rules and fact.

Step 3: According to the distance, the membership for each task intention can be calculated as:

$$m = \frac{\sum\limits_{i=1}^{3} m^i \prod\limits_{j=1, j\neq i}^{3} d^i}{\sum\limits_{i=1}^{3} \prod\limits_{j=1, j\neq i}^{3} d^i} \quad i = 1, 2, 3 \tag{4}$$

By Equation (4), the assistance movement of ILSR was planned. However, considering the intention of stop or doing nothing, $\boldsymbol{Rule}^4$ should be identified separately to make an identification of user's stop intention. The satisfaction of antecedent of $\boldsymbol{Rule}^4$ was tested by d^i $(i = 1, 2, 3)$.

$$l = \arg \min_{i=1,2,3}\left(d^i\right) \tag{5}$$

If $d_l \leq d_{threshold}$, user is doing vacuuming, and the assistance motion of ILSR is m.

Else user is doing something else or nothing, and assistance motion of ILSR is m^4.

In this work, $d_{threshold}$ was set as 0.25. $d_{threshold}$ depends on the maximum value when user was implementing the vacuuming task. In order to distinguish the moving action and still posture, the parameter k is set as 4.0 in this work.

4. **Vacuuming Assistance Experiment.** In order to verify the performance of proposed assistance method for vacuuming task, a vacuuming assistance experiment was executed. In the experiment, 4 piles of rubbish were fixed in the field, which is flat square ground with 2 *meter* width as shown in Figure 6. 4 piles of rubbish were labelled by $R1$, $R2$, $R3$ and $R4$ with the position of (1.0m 0.5m), (0.3m 0.9m), (1.0m 1.8m), and (1.75m 1.6m) in reference coordinates respectively. The start point was in the position of (1m, –0.15m). 2 male subjects with 1.80m and 1.69m height respectively were required to perform the experiments. They were instructed to do vacuuming in their own intention for 4 times, respectively.

The assistance trajectory of one of experiments for subject 1 is shown in blue solid line in Figure 6. The yellow triangles represent the orientation of ILSR during the experiment.

In Figure 7, the gesture of right forearm is shown. During the first 8 seconds in Figure 7, subjects were required to keep in still, so there is no changing of gesture of their right forearms. ILSR moved forward with turning left slowly at the beginning. When subject had cleaned up $R1$, he turned to clean $R2$ at the 15th second naturally and ILSR turned left immediately with low advancing speed. It can be found that, the gesture of right forearm changed suddenly around the 13th second. Similarly, for $R3$ and $R4$. ILSR assisted subject to move forward and turn right simultaneously until subject approached the position. In Figure 7, the gesture changing can be found at the 21st second and the 32nd second. At these 2 moments, the subject changed his gesture for $R3$ and $R4$. Finally, after subject finished the task, he stopped vacuuming and ILSR stopped moving and waited for user's next moving intention. The vacuuming motion of subject 1 was shown in (a), (b), (c) and (d) of Figure 6.

In Figure 8, reasoned assistant movement of ILSR is depicted as orange solid line and the real movement of ILSR in body coordinate is presented by blue dot line. (a) of Figure 8 shows the moving velocity of Y axis of ILSR body coordinate $\Sigma(x_b, y_b, C)$. As shown in the graph, the moving velocity decreased around the 13th, 21st and 32nd, 47th second. In these timings, subjects changed their vacuuming action for other cleaning target. Similarly, at the same timings, the angular velocity of ILSR (measured angular velocity of ILSR $\dot{\theta}_m$, planned angular velocity of ILSR $\dot{\theta}$) increased gradually for adjusting the orientation of ILSR so that subjects can clean the position in a convenient and natural gesture. Comparing the reasoned motion of ILSR and real motion of ILSR by orange solid line and blue dot line, it can be found that some tracking errors existed during the

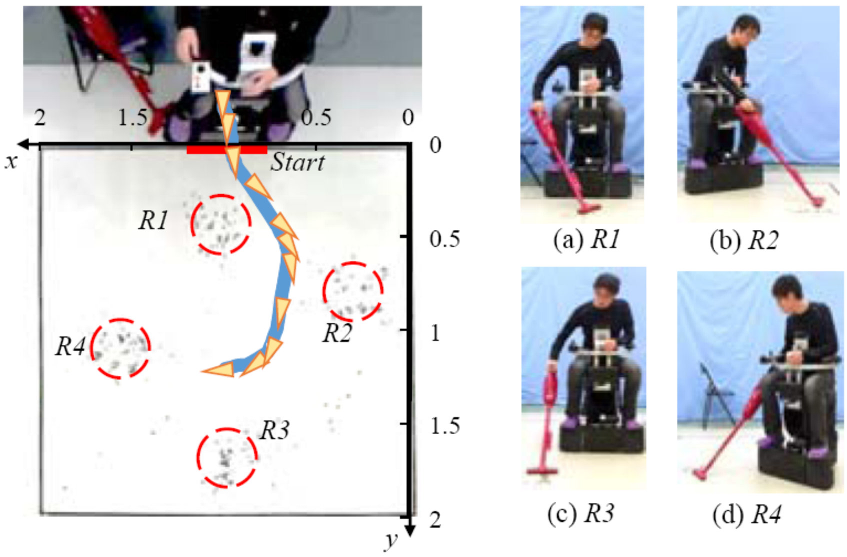


Figure 6. Vacuuming assistance experiment

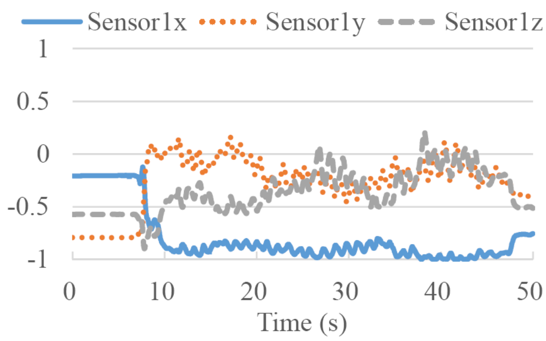
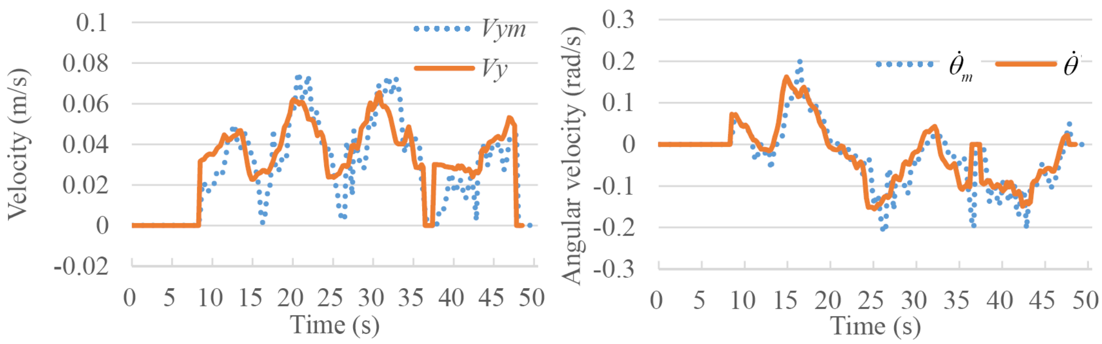


Figure 7. Motion of right forearm



(a) Velocity in Y axis of body coordinate (b) Angular velocity of ILSR

FIGURE 8. Reasoned and measured movement of ILSR in body coordinate

TABLE 2. Vacuuming time for 2 subjects

	Subject 1	Subject 2
Height	1.80m	1.69m
Time of Exp.1	68s	67s
Time of Exp.2	56s	69s
Time of Exp.3	66s	76s
Time of Exp.4	60s	77s
Average Time	62.5s	72.25s

vacuuming assistance experiment. In this paper, open-loop control method was applied in the control of ILSR; therefore, there were speed tracking errors for the planned movement of ILSR. In future work, a close-loop control method will be applied to improving the precision of intention velocity tracking.

In each experiment, there are 200 pieces of paper rubbish were set on the experiment field. When subjects finish the vacuuming task, and the left number of paper rubbish was counted for evaluating the compliment of vacuuming task.

The experiment results are shown in Table 2. For subject 1, the average time for finishing the vacuuming was 62.5 seconds, 10 seconds shorter than 72.25 seconds for subject 2. The reason is the taller height of subject 1 made him accessible for wider range of task field. Both of them can perform the vacuuming task under the assistance of the proposed method.

5. **Conclusions.** A vacuuming assistance method on ILSR was proposed in this paper. By reasoning user's task intention with upper-body motion information, assistance movement of ILSR can be planned based on the proposed method. By this assistance method, subjects can focus on performing vacuuming task only, and the ILSR can make movement in his/her intention as they move by their own legs. In the vacuuming assistance experiment, it was shown that the proposed method can provide proper assistance for user's vacuuming task practically. For future work, more daily tasks will be studied, in order to provide more ADL tasks assistance for the lower-limb handicapped by ILSR and the experiments based on the lower-limb handicapped will be implemented.

Acknowledgment. This work was supported by JSPS KAKENHI Grant Number 24300 203 and the Canon Foundation.

REFERENCES

[1] B. Shen and S. Wang, Real-time identification of user's activity of daily living by distance type fuzzy reasoning method, *ICIC Express Letters*, vol.10, no.2, pp.527-534, 2016.

[2] S. Y. Wang, K. Ishida and M. Fujie, A multi-function type human support robot for independent living, *Proc. of the 23rd Annual Conference of BMFSA*, pp.227-228, 2010.
[3] J. L. Jones, Robots at the tipping point: The road to iRobot Roomba, *IEEE Robot. Autom. Mag.*, vol.13, no.1, pp.1-3, 2006.
[4] K. Tanaka, K. Matsunaga and H. O. Wang, Electroencephalogram-based control of an electric wheelchair, *IEEE Trans. Robotics*, vol.21, no.4, pp.762-766, 2005.
[5] L. Wei, H. Hu and Y. Zhang, Fusing EMG and visual data for hands-free control of an intelligent wheelchair, *Int. J. Humanoid Robot*, vol.08, no.4, pp.707-724, 2011.
[6] P. Jia, H. H. Hu, T. Yuan and K. Lu, Head gesture recognition for hands-free control of an intelligent wheelchair, *Industrial Robot*, vol.34, pp.60-68, 2007.
[7] S. Y. Wang, T. Tsuchiya and M. Mizumoto, Distance-type fuzzy reasoning method, *J. Biomed. Fuzzy Syst. Assoc.*, vol.1, no.1, pp.61-78, 1999.